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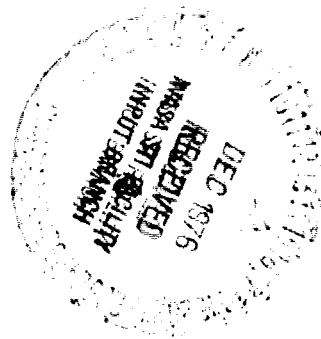
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**THE REDOX FLOW SYSTEM FOR SOLAR
PHOTOVOLTAIC ENERGY STORAGE**

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ABSTRACT

A new method of storage has been applied to a solar photovoltaic system. The storage method is a Redox Flow System which utilizes the oxidation-reduction capability of two soluble electrochemical redox couples for its storage capacity. The particular variant described here separates the charging and discharging function of the system such that the electrochemical couples are simultaneously charged and discharged in separate parts of the system. The solar array had 12 solar cells; wired in order to give a range of voltages and currents. The system stored the solar energy so that a load could be run continually day and night. Two of the main advantages of the Redox System are that it can accept a charge in the low voltage range and produce a relatively constant output regardless of solar activity.

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SUMMARY

The interfacing of a Solar Photovoltaic System and a Redox Flow System for storage was workable. The Redox Flow System, which utilizes the oxidation-reduction capability of two redox couples, in this case iron and titanium, for its storage capacity, gave a relatively constant output regardless of solar activity so that a load could be run continually day and night utilizing the sun's energy. One portion of the system was connected to a bank of solar cells to electrochemically charge the solutions, while a separate part of the system was used to electrochemically discharge the stored energy.

INTRODUCTION

Intermittent electrical power sources, such as wind and solar, operating independently of utility ties, need an electrical storage device or system in order to have acceptable time independent functional characteristics. This paper describes the combination of Redox Flow Cell energy storage with solar photovoltaic cells to provide a continuous supply of electrical power. The electrochemical charge and discharge functions are separated such that the system can undergo charge and discharge at the same time without the requirement for extensive electronic circuitry.

To our knowledge this is the first application of a storage device other than a conventional battery to be used with an intermittent solar electrical generating system.

THE STORAGE DEVICE

The storage device is called a Redox Flow Cell. As the name implies it is an electrochemical storage device which utilizes the oxidation and reduction of two electrochemical couples for charging and discharging. Rechargeable redox cells are not a new concept and several variations are described in the literature, though none have been commercially developed to date. The idea of using this particular type of system for energy storage is new and was initiated at the NASA Lewis Research Center (LeRC) as part of a project to develop Redox cells for energy storage applications by the Energy Research and Development Administration (ERDA). Further details on the Redox System concept can be obtained from references 1 to 3.

A diagram of a Redox System of the type being developed at NASA LeRC is shown in Figure 1. It consists of two tanks of fluid (one for the anode and another for the cathode), a power conversion section where the solutions react electrochemically to produce electric current on dis-

charge or are recharged and a recirculating pump. The power conversion section requires an ion selective ionically conducting membrane to prevent direct chemical reaction of the two solutions. The development of a membrane with appropriate properties is a major part of the ongoing research and development work on the Redox System concept.

The couples used for the work described here were iron (Fe III/Fe II) and titanium (Ti III/TiO²⁺) as concentrated acid chlorides in water. The theoretical voltage for this combination is ~0.68 volt. It is desirable to have higher voltage couples and if chromium (Cr II/Cr III) could be used with iron ~1.2 volts could theoretically be achieved.

A schematic of the storage system used with the solar array is shown in Figure 2. In this case separate redox cells were used for discharging and charging. The cells measured approximately 3 by 6 inches. The electrolyte solutions (1 molar chloride salts dissolved in 6 molar hydrochloric acid) flowed by gravity from the 2000 ml reservoirs into the discharging cell, through a chamber to break the electrolytic contact between the charging/discharging cells and into the charging cell. A pump recirculated the solutions to the reservoirs at 10 ml/minute. Five hundred milliliters of solution in each reservoir provided a storage capacity of 12 ampere hours.

THE SOLAR ARRAY

A schematic of the solar array is shown in Figure 3. It consisted of 14 circular (22.8 cm²) silicon solar cells covered with an FEP film. The cells were mounted on an aluminum plate which was mounted on the roof of the building facing South and inclined at 25° to the horizontal. Cells 1 and 2 on the figure were used only to operate a meter relay which switched the remaining 12 cells in and out of the circuit. This prevented back discharging through the array since no diode was in the circuit. The array was arranged so that the solar cells could be switched in as doublets or triplets in series. Each set of doublets or triplets could be placed in parallel with one, two, or three other sets. This enables one to have a range of voltages and currents available. The upper limit placed on the voltage prevented electrolytic decomposition of the electrolyte solution into hydrogen and chlorine gases on charging.

The array was instrumented with copper-constantan thermocouples. One to measure the ambient temperature and one to measure the working solar cell temperature. These values usually differed by about 15° C with the array cells reaching a maximum temperature of 48° C.

THE ELECTRICAL SYSTEM

The electrical system diagram is shown in Figure 4. Note that the charge and discharge circuitry of the system are isolated from each other. The four pen recorder traced the charging voltage and current and the discharging voltage and current. The switching device and the digital voltmeter allowed direct reading of any of these values instantaneously. The ampere hour integrators recorded the total integral of the current times the time. This enables one to calculate the ampere-hour efficiency of the system.

A complete picture of the Test Stand is shown in Figure 5.

RESULTS AND DISCUSSION

The results show that the combination of the Redox energy storage system using separate cells for charging and discharging the redox solutions with solar photovoltaic cells was entirely satisfactory. The separation of the charging and discharging functions eliminates the need for any complicated load sharing electronics.

A typical charge-discharge profile is shown in Figure 6. Note that the Redox system accepts charge at very low voltages (point A at about 6 A. M.). Also to be noted is the flat output from the system, even through periods of solar cell fluctuations, point B.

No interfacing problems were encountered with this system, and the system was run continuously for 2 months. The main advantages identified for the storage system are:

1. The storage capacity is determined by the amount and concentration of solution in the reservoirs (see Refs. 1 and 2).
2. It has the capability of accepting charge under variable voltage conditions.
3. The output is relatively constant regardless of solar intensity.
4. Modular design and separation of the power and storage function makes it easy to adopt to different requirements of power and storage capacity.
5. Cell stacking for higher voltages is possible.
6. Continuous load operation from an intermittent source is possible without complex interfacing.
7. No cycle life limitations are present in theory.
8. Deep discharges are possible.

The particular mode of operation described here was chosen for: (1) continuous load operation, and (2) most efficient utilization of the sunlight.

Optimization for different circumstances can be

achieved by varying the size of components and concentrations and volumes of solutions. Research and development work is in progress to establish the technical and cost feasibility of Redox Flow Cells as an electrical storage option for solar photovoltaic arrays, wind turbines, and central station (or dispersed) utility bulk storage or peaking applications.

REFERENCES

1. L. H. Thaller, "Electrically Rechargeable Redox Flow Cells," Ninth Intersociety Energy Conversion Engineering Conference, p. 924, 1974.
2. M. Warshay and L. O. Wright, "Cost and Size Estimates for an Electrochemical Bulk Energy Storage Concept," NASA TM X-71805, 1975.
3. P. R. Prokopius, "Model for Calculating Electrolytic Shunt Path Losses in Large Electrochemical Energy Conversion Systems," NASA TM X-3359, 1976.

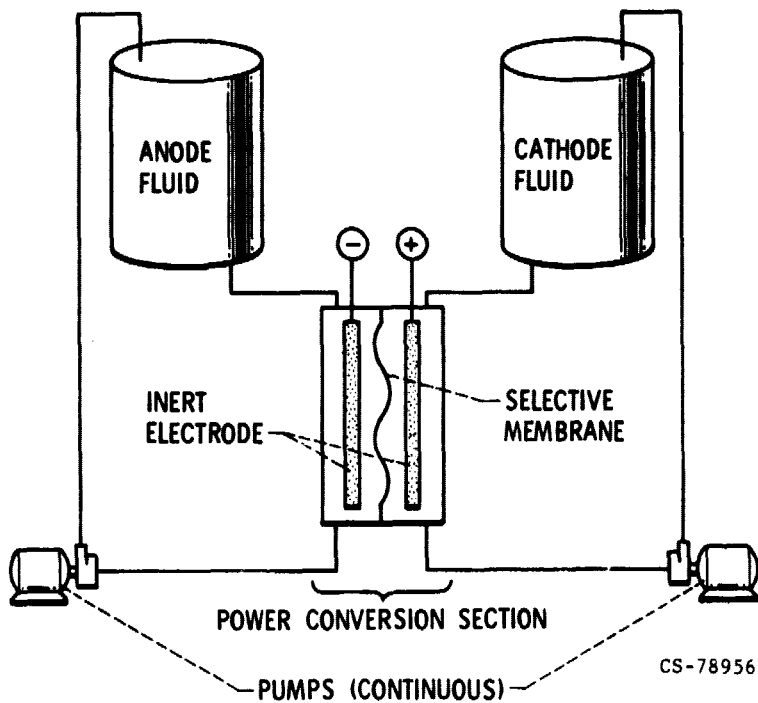


Figure 1. - Redox system.

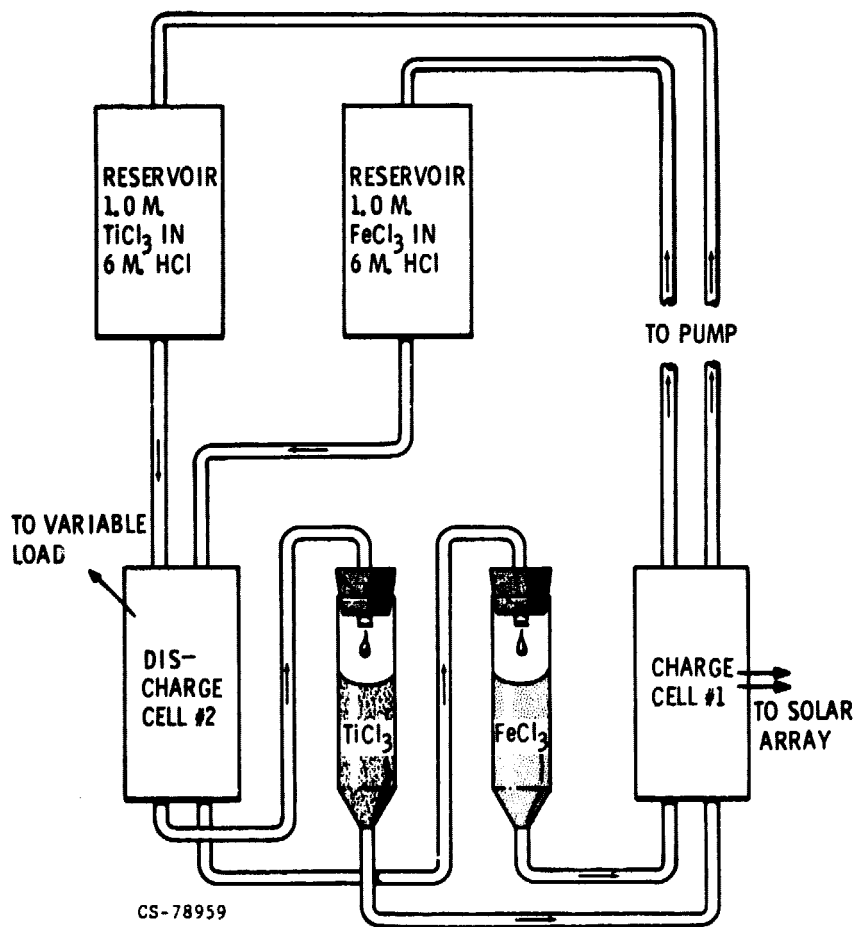


Figure 2. - Schematic of the storage system.

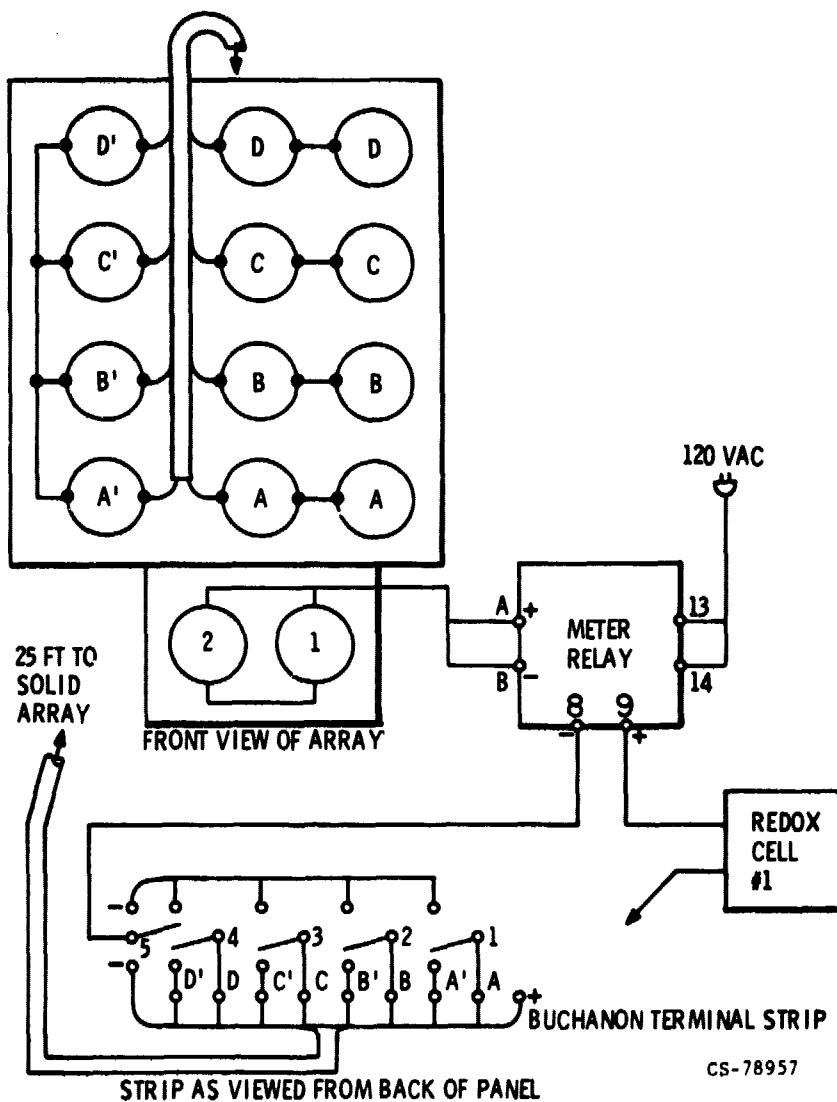
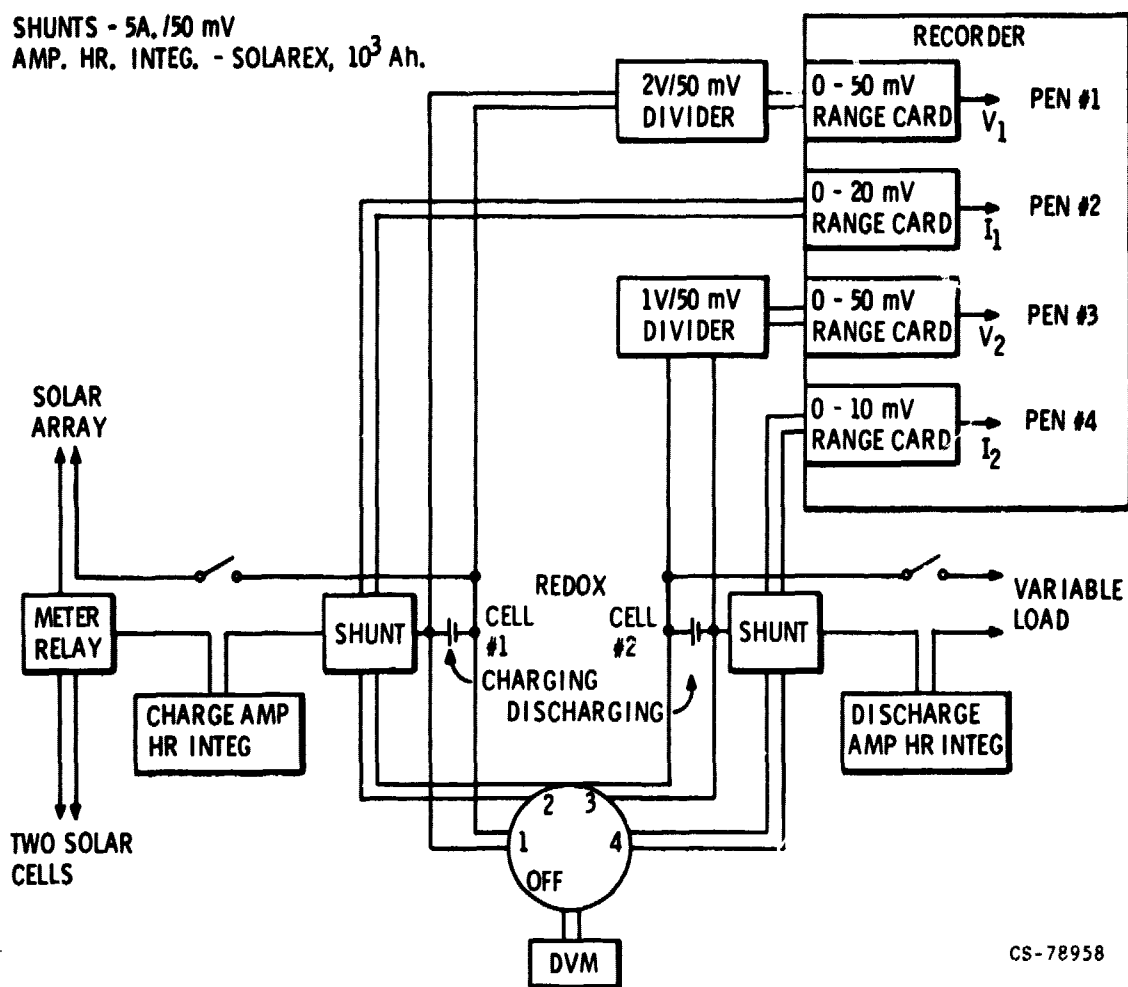


Figure 3. - Schematic of solar array.

SHUNTS - 5A, 150 mV
 AMP. HR. INTEG. - SOLAREX, 10^3 Ah.



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Figure 4. - Electrical system.

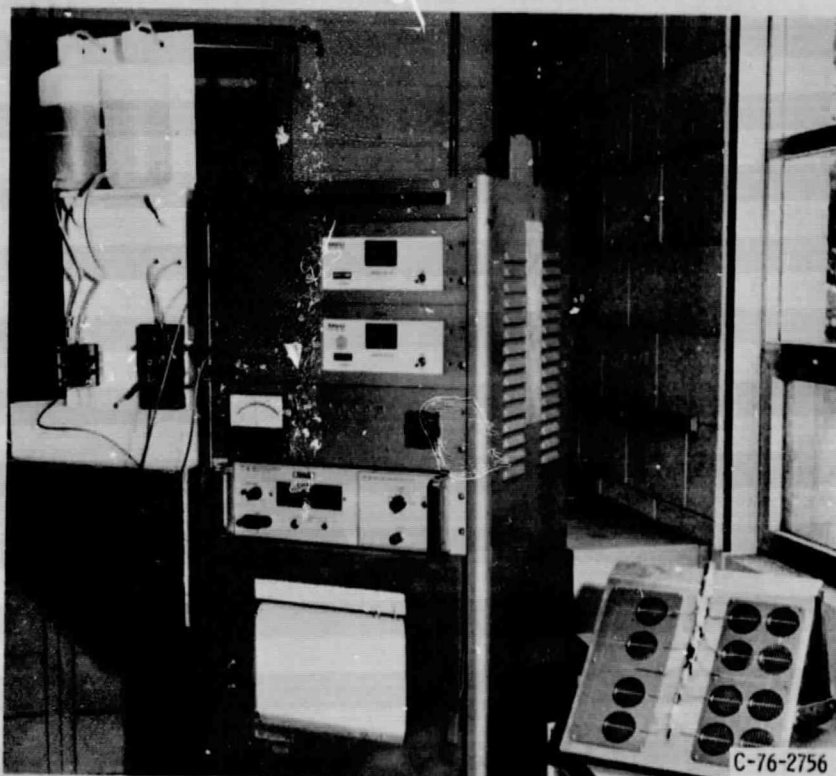


Figure 5. - Test stand.

V_1 CHARGE CELL VOLTAGE
 I_1 CHARGE CELL CURRENT
 V_2 DISCHARGE CELL VOLTAGE
 I_2 DISCHARGE CELL CURRENT

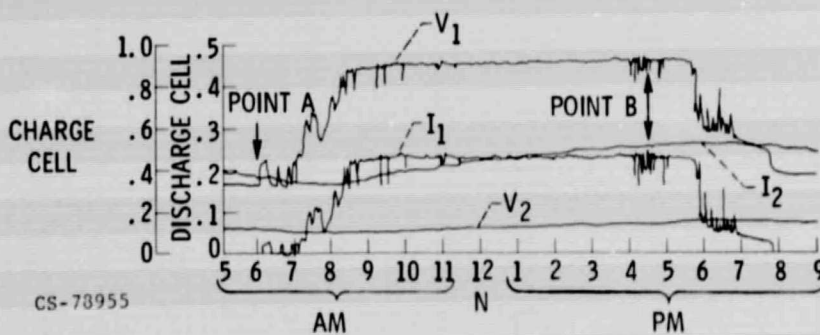


Figure 6. - Charge-discharge profile.